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# Perspectives of SM Higgs measurements at the LHC

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**Abstract.** The latest unsuccesful Higgs searches at LEP have pushed its mass well into the domain where significant signals can be expected from the LHC experiments. The most sensitive LHC Higgs signatures are reviewed and the discovery year is estimated as a function of the Higgs mass. Finally, we give some ideas about: 'What might be known about the production and decays of a SM Higgs boson' after 10 years of LHC?

**Keywords.** Large hadron collider; Higgs.

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## 1. Introduction

The Standard Model (SM) of particle physics has survived [1] not only the Y2K millennium bug, but also many years of precision electroweak physics at high energies.

With the observation of the top quark, with a mass of $\approx 175 \pm 5$ GeV, and within the SM, the Higgs boson became the 'last' undiscovered particle. Assuming that the Higgs boson is the only missing particle up to very high energy scales $\Lambda$, the mass of the SM Higgs can be constrained from a phenomenological approach [3], as shown in figure 1. Assuming that the SM is valid up to the Planck scale, one finds that the Higgs mass should be $\approx 160 \pm 20$ GeV [4].

The SM Higgs mass can also be constrained from the different electroweak precision measurements, assuming that no other new physics contributes to the values of the observables. One finds that the best description of all high energy data is obtained for a Higgs mass of 77 GeV with an upper limit of $\approx$ 215 GeV at 95% confidence level, using a $\chi^2$ variation of four [5]. This 'limit' ignores however that the best SM fit has a $\chi^2$ of 23 for 15 degrees of freedom. This $\chi^2$ corresponds to a probability that the SM with this Higgs mass describes the data of $\approx$ 10% for the minimum and to $\approx$ 2% for the estimated upper limit.

More solid results come from direct Higgs searches at LEP. The latest preliminary results from the LEP experiments and the 1999 data indicate with 95% confidence level that the mass of the SM Higgs must be heavier than $\approx$ 103–108 GeV [6]. The combined candidate mass spectrum does not indicate any significant excess. It seems thus rather unlikely that the existing exclusion limits can be turned into a five standard deviation discovery.

The stage for the Higgs search is thus almost 'ready' for the appearance of the ATLAS and CMS experiments at the LHC. The LHC, a 14 TeV proton–proton collider at CERN,

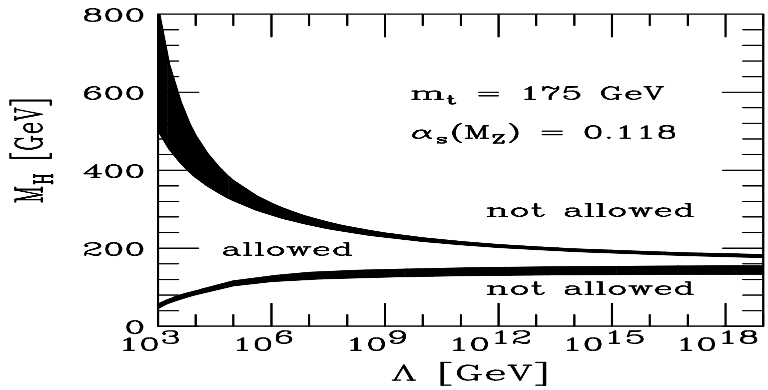


**Figure 1.** The area between the two black curves shows the allowed Higgs mass range assuming the validity of the Standard Model up to a scale $\Lambda$ [3].

is currently scheduled to start at the earliest in the summer of the year 2005. LHC Higgs search strategies have been discussed at many places and reviews [7]. Consequently, the best SM Higgs discovery signatures for masses between 110–700 GeV are assumed to be well known. After reminding the reader of the main signatures, we speculate about the year when the Higgs will be discovered. This is followed by a discussion of what can be learned at the LHC about the production and decays of a SM Higgs boson.

## 2. The 'well' known

Recent LHC Higgs cross-section estimates for the different production mechanisms can be found in [8]. By far the largest contribution to the cross-section comes from the gluon–gluon fusion process to top quarks [9], which is directly sensitive to the $t\bar{t}H$ coupling. The second substantial contribution comes from the $WW$ and $ZZ$ boson fusion process $qq \to qqH$ which is sensitive to Higgs couplings with massive vector bosons. In addition, for Higgs masses below 200 GeV, the associated production $W(Z)H$ and $t\bar{t}H$ has a sizeable cross-section. To investigate the sensitivity to a particular Higgs signature, the total cross-section has to be multiplied with the various branching ratios. Figure 2 shows estimated $\sigma \times BR$ for the most promising Higgs search modes. Only the decays $H \to \gamma\gamma$ and $H \to ZZ^{(*)} \to 4\ell^{\pm}$, which have a small detectable cross section, can be seen as narrow mass peaks.

The third signature, $H \to WW^{(*)} \to \ell^+\nu\ell^-\bar{\nu}$ does not give a narrow mass peak but has a substantial cross-section. The analysis described in reference [11] demonstrated that the particular kinematics of this reaction, using the rapidity distribution and $WW$ spin correlations, allows especially for Higgs masses between 155–180 GeV, to measure backgrounds from the data.

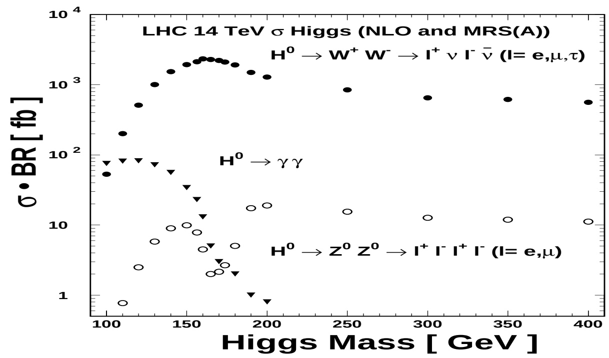


**Figure 2.** Expected $\sigma \times BR$ for different detectable SM Higgs decay modes [10].

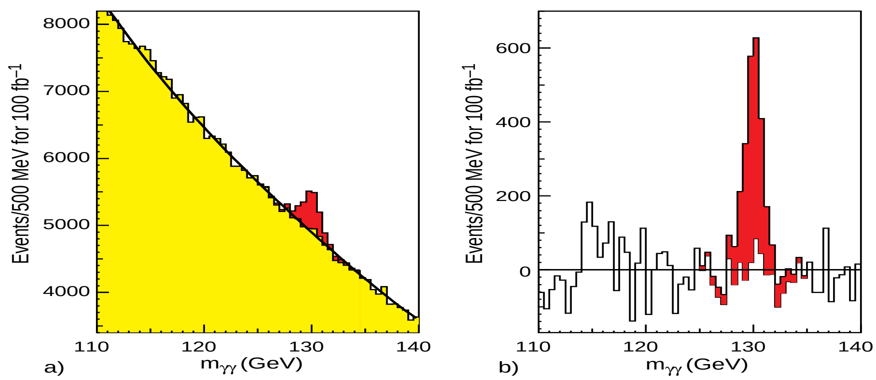


**Figure 3.** CMS simulation [13] for the Higgs with a mass of 130 GeV before and after background subtraction for the decay $H \to \gamma\gamma$.

## 2.1 *Higgs searches with narrow mass peaks*

The Higgs search where narrow mass peaks can be reconstructed is limited to the decays into $H \to \gamma\gamma$ and $H \to ZZ^{(*)} \to 4\ell^{\pm}$. Expected mass distributions for these Higgs decay modes from CMS are given in figure 3 [13] for a Higgs mass of 130 GeV and in figure 4 for masses of 300 GeV and 500 GeV [14]. According to this CMS study, a SM Higgs with a mass of 130 GeV can be seen in the $\gamma\gamma$ channel with a signal of 2500 events above a smooth continuum background of about 30000 events and an integrated luminosity of 100 fb$^{-1}$ using NLO cross-sections. For Higgs masses larger than 200 GeV one expects narrow Higgs mass peaks from the $4\ell^{\pm}$ final state. For example, recent studies from ATLAS [15] show that a Higgs with a mass of 400 GeV should be seen with 27 signal events (LO cross-section) above a continuum background of $\approx$ 10 events and a luminosity of 10 fb$^{-1}$.

Decays of $W$ and $Z$ to $q\bar{q}(g)$ can also be used to reconstruct mass peaks. Unfortunately, accurate measurements of jet 4-vectors are especially difficult at the LHC and so far no simulation analysis could demonstrate 'discovery' signatures with Higgs decays into jets.

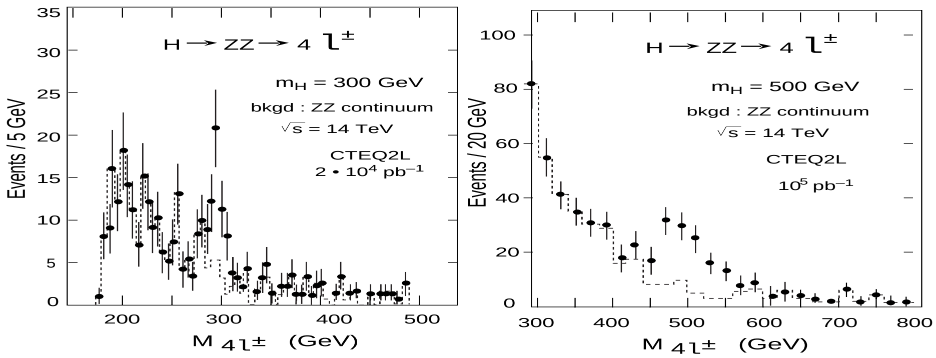


**Figure 4.** CMS simulation results for $H \to ZZ \to \ell^+\ell^-\ell^+\ell^-$ and $M_H = 300$ GeV and $M_H = 500$ GeV.

### 2.2 *Higgs searches without narrow mass peaks*

Especially for Higgs masses between 155–180 GeV, the $4\ell^{\pm}$ signature suffers from very low branching ratios and five standard deviation signals require high luminosities of at least 30–100 fb$^{-1}$.

However, the channel $H \to WW(^*) \to \ell^+\nu\ell^-\bar{\nu}$, following the analysis method described in ref. [11], provides now the most promising signature for masses between 155–180 GeV. The proposed Higgs strategy for masses below 200 GeV selects events which have two isolated leptons (electrons or muons) and no jets. The main criteria to separate signal and background use: (a) The shorter rapidity plateau of signal $gg \to H \to WW$ events compared to continuum $q\bar{q} \to WW$ background events; (b) the small opening angle between the two charged leptons which originates from the V–A structure of $W$ decays and the different $WW$ spin correlations for signal and background and (c) the lepton transverse momentum spectrum which depends strongly on the $W p_t$ spectrum, the $WW$ mass and thus also on the Higgs mass.

The expected small opening angle between the two charged leptons for signal events and Higgs masses below 200 GeV allows to determine the backgrounds from dilepton events with larger opening angles. A further enhancement of signal events with respect to backgrounds can be obtained from a detailed analysis of the lepton $p_t$ spectra which result in clear signals for masses between 150–180 GeV and some enhancements for other Higgs masses. Following the suggested criteria, signal to background ratios of about 1:1 are obtained for Higgs masses between 150–180 GeV and significant signals require luminosities of only 1–2 fb$^{-1}$. Examples for the lepton $p_t$ spectra from signal and backgrounds are shown in figure 5 for a luminosity of 30 fb$^{-1}$ and Higgs masses of 170 GeV and 250 GeV. For Higgs masses smaller than 140 GeV or larger than 200 GeV, the proposed selection criteria give statistical significant signals but only with small signal to background ratios shown in figure 6.

For Higgs masses above 500 GeV, the natural width becomes quite large and the experimental mass resolution becomes less important. Therefore, other signatures like $pp \to H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ and events with hadronic $W$ and $Z$ decays and

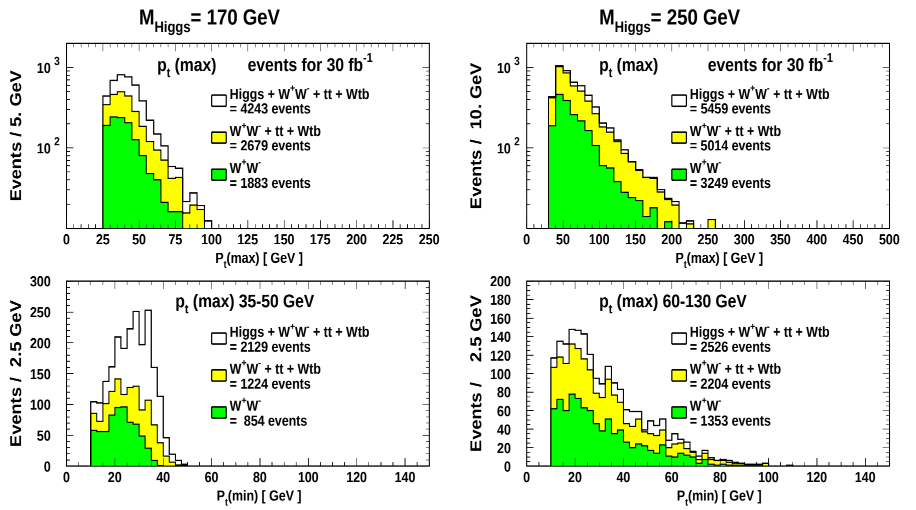


**Figure 5.** Expected lepton $p_t$ spectra for $H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$ and masses of 170 GeV and 250 GeV. The signal is superimposed to various SM backgrounds.

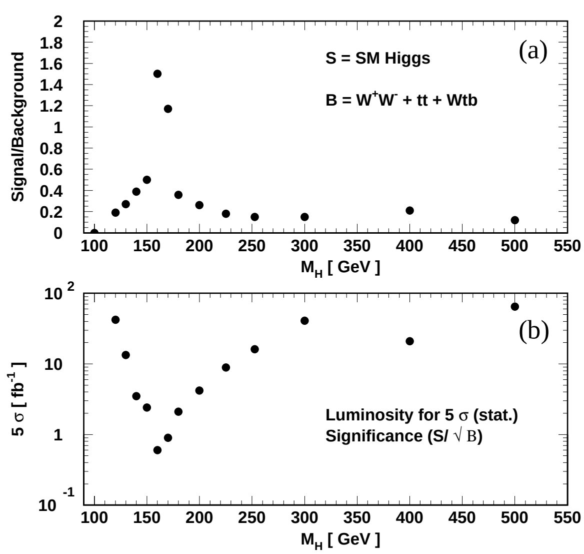


**Figure 6.** SM Higgs signal over background ratio (**a**) and (**b**) the required luminosity to obtain a 5 standard deviation statistical significance signal with $pp \to H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$ for $M_H$ between 120 GeV and 500 GeV.

with additional 'forward' jets from the reaction $qq \to Hqq$ with $H \to W^+W^- \to \ell^+\nu q\bar{q}$ give, despite the absence of narrow peaks, promising and competitive Higgs signals as shown in figure 7.

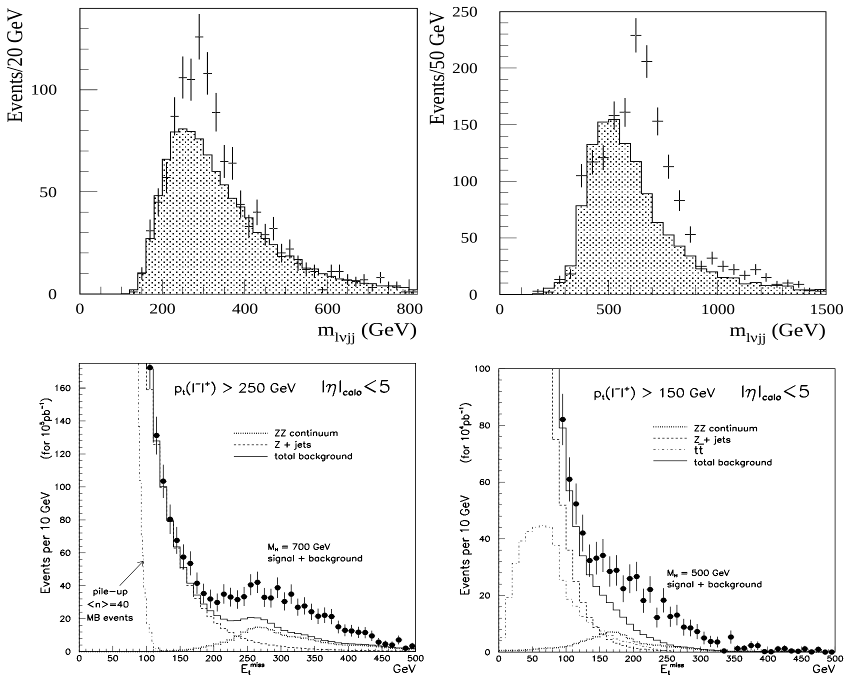


**Figure 7.** ATLAS simulation results [15] for $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ with a Higgs mass of 500 GeV ($L = 10$ fb$^{-1}$) and 700 GeV ($L = 100$ fb$^{-1}$) and for $qq \to qqH$ with $H \to WW \to \ell\nu q\bar{q}$ and Higgs masses of 300 GeV ($L = 30$ fb$^{-1}$) and 600 GeV ($L = 100$ fb$^{-1}$).

## 3. When are we seeing the Higgs?

According to todays schedule, the LHC and its experiments are expected to start data taking in the summer of 2005. During the following years one expects LHC peak luminosities of $10^{33}$ cm$^{-2}$ sec$^{-1}$, corresponding to produced integrated luminosities of $\approx$ 10 fb$^{-1}$ per year. After some years of experience with the machine one hopes for peak luminosities of $10^{34}$ cm$^{-2}$ sec$^{-1}$. Usual estimates assume that integrated experimental luminosity of 30 fb$^{-1}$ are collected with the initial peak luminosity followed by some years of high luminosity running resulting in an integrated luminosity of perhaps 300 fb$^{-1}$ after 10 LHC years. To guess the year of the LHC Higgs discovery one has to assume some ‘realistic’ running of the LHC and its big experiments. In absence of better estimates we propose a simple minded guessing, following the experience with LEP.

Starting with year 0 (the 2005 running in) of LHC, year 0, 1 and 2 will give 0.1, 1.0 and 5.0 fb$^{-1}$ per experiment respectively. Years 3, 4 and 5 will give each about 10 fb$^{-1}$. This will be followed by the high luminosity LHC phase, allowing for an integrated luminosity of 100 fb$^{-1}$ at the end of year 6. Finally, years 7–10 will give an integrated luminosity of 300 fb$^{-1}$ per experiment by the year 2016.

Asking for a Higgs signal which results in a five standard deviation excess above background, one can take SM cross-section estimates (NLO) for signal and backgrounds and

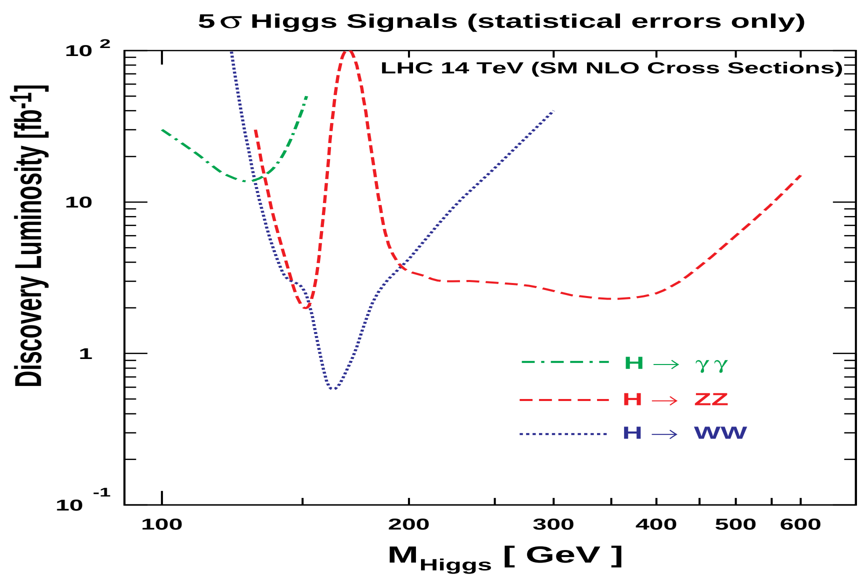


**Figure 8.** Required luminosity to discover the Standard Model Higgs with a statistical significance of five standard deviations in the mass range between 100–700 GeV at the LHC.

the most optimistic estimates from ATLAS and CMS to calculate the required luminosity. The results, using Poisson statistics, are shown in figure 8 as a function of the Higgs mass. A SM Higgs with a mass between ≈ 140–500 GeV might thus be observed during the first two real years of the LHC. If no signal appears in this mass range, one should find at least some regions for masses below 140 GeV or above 500 GeV with excess events coming either from the Higgs or from background fluctuations. It should also be possible to exclude, at the 95% confidence level, large regions of the remaining mass regions. If a Higgs exists in some of these excess regions, one has to wait most likely for the year 2010 to observe a five standard deviation excess in a single channel [12].

## 4. Once the Higgs has been discovered

About 10 years of direct Higgs searches at LEP and detailed simulation Higgs studies for the LHC give confidence that a Higgs boson with SM-like couplings will be discovered at the LHC. The obvious next question is how well the Higgs sector can be tested at the LHC. We restrict the discussion of this question to the SM Higgs, as a more general discussion depends so strongly on the Higgs mass and the preferred model. A detailed discussion about the LHC measurements for Higgs masses smaller than 200 GeV can be found in [16].

Assuming that the Higgs will be found as a narrow mass peak one knows immediately and almost automatically the Higgs mass with a relative precision of about 1% or better. For masses where either the natural width is large or where the mass has to be measured indirectly using for example the lepton $p_t$ spectra one should still be able to obtain the mass with an accuracy of a few %. The ATLAS collaboration has estimated that, using 300 fb$^{-1}$, mass accuracies of about 0.1% can be achieved over the entire mass range [15]. It seems however that the Higgs mass accuracy obtained together with the discovery is more than sufficient to test the consistency of the SM from precision observables. Within the SM, the natural Higgs width is up to relatively high masses much smaller than the experimental resolution at the LHC. Measurements of different Higgs production and decay modes are therefore required to extract informations about the Higgs couplings.

The discovery of the Higgs, with a cross-section consistent with the gluon–gluon fusion process, will provide the first information that the product of the $t\bar{t}H$ and $HWW(ZZ)$ couplings is within $\approx \pm$20% consistent with the SM. Furthermore, once the Higgs mass is known, it becomes much easier to separate other signatures from backgrounds [17]. It might thus be interesting to re-investigate systematically the potential signals from different Higgs signatures, assuming that the Higgs mass is already known.

### 4.1 *Additional Higgs signatures*

In the absence of such systematic studies, we summarize here some qualitative ideas about the various signatures:

- The gluon–gluon fusion process $gg \to H$ provides essentially the Higgs discovery signature for the Higgs decays $H \to \gamma\gamma$, $H \to ZZ$ and $H \to WW$. For Higgs masses below 140 GeV the decays into $b\bar{b}$ and $\tau^+\tau^-$ are dominant but appear to be undetectable for SM Higgs cross-sections.

  However, a recent study shows that Higgs candidates selected with the $\gamma\gamma$ signature with high $p_t$ and which are balanced by a jet have very different kinematics for a Higgs signal and for the background processes [19]. Consequently, paying the price of much smaller signal efficiency, the proposed criteria allow to improve dramatically the signal to background ratio. Following these ideas, new criteria might exist which allow to observe signals for other Higgs decay modes.
- The particular signature of $WW$ and $ZZ$ boson fusion process $qq \to Hqq$ comes from additional large rapidity jets which can be tagged. The potential of this signature has been advocated already in 1987 [20].

  According to todays Monte Carlo simulations, such forward jet tagging gives very strong background reductions and good signal efficiencies for high masses. Details about recent simulation studies from ATLAS can be found in [15]. With the strongly reduced backgrounds, the detection of Higgs bosons with masses above $\geq$ 300 GeV, decaying into $H \to WW \to \ell\nu q\bar{q}$ and $H \to ZZ \to \ell\ell q\bar{q}$ looks competitive with the 'known' discovery channels as can be seen from a comparison of figures 4 and 7.

  In addition to the promising results for large Higgs masses, significant parton level signals for Higgs masses below 200 GeV have recently been obtained [21] for the decays $H \to \gamma\gamma$, $H \to \tau\tau$ and $H \to WW \to e\nu\mu\nu$.
- Finally the associated Higgs production $q\bar{q} \to WH(ZH)$ and $gg \to t\bar{t}H$ with Higgs decays into $\gamma\gamma$, $b\bar{b}$ and $\tau\tau$ might result into detectable signals. Very low rate signals of 10–20 events have been shown for leptonic $Z$ and $W$ ($t \to Wb$) decays combined with Higgs decays into $\gamma\gamma$ and 100 fb$^{-1}$ [15]. Simulations of the

channels $q\bar{q} \to WH \to WWW$ with fully leptonic $W$ decays [22] and $gg \to t\bar{t}H$ with $H \to b\bar{b}$ indicate also promising signals [15].

### 4.2 *Higgs production and decay, what can be measured?*

According to the above arguments, assuming that the Higgs mass will be known from the discovery channel and with an integrated luminosity of more than 100 fb$^{-1}$, the following scenario can be envisaged:

(1) The inclusive Higgs production cross-section, dominated by the gluon–gluon fusion process, can be measured from the discovery channels with 500–1000 events above backgrounds, corresponding to a statistical accuracy of about ±3–5%. These signals should allow to measure (a) the cross-section as a function of the Higgs $p_t$ with ± 20% accuracies up to transverse momenta of ≈ 100–150 GeV and (b) to obtain first quantitative information about the polarization of the $W$ or $Z$ bosons.

(2) Using the known Higgs mass, it should become possible to observe signals for the inclusive Higgs production with Higgs decays to $WW$ and $ZZ$ and masses above 140 GeV. Such signals give cross-section independent results for the corresponding relative Higgs branching ratios with accuracies of 5–10%.

(3) The known Higgs mass should also help to establish Higgs signals in the $WW$ and $ZZ$ boson fusion reaction and the associated production $t\bar{t}H$ channel. For Higgs masses above 140 GeV, signals might be seen with several $W$ and $Z$ decays. For example, the ATLAS studies of this process show that a Higgs with a mass of 600 GeV, decaying into $WW \to \ell\nu q\bar{q}$ should give signals between 400–1000 events for 100 fb$^{-1}$ depending on the jet tagging criteria. For Higgs masses below ≈ 140 GeV, promising parton level signals with 50–100 events for 100 fb$^{-1}$ above background have been shown for $H$ decays to $\gamma\gamma$ and $\tau\tau$.

(4) The ratio between Higgs signals seen with the gluon–gluon dominated inclusive Higgs production and with the vector boson fusion production and the same decay modes probes the relative coupling strength between $t\bar{t}H$ and $WW(ZZ)H$. Using the above numbers it should be possible to measure this ratio with accuracies of ≈ 5–10%. For Higgs masses below 140 GeV additional information should come from the associated Higgs production $t\bar{t}H$ with the decay $H \to \gamma\gamma$ and $H \to b\bar{b}$.

## 5. Summary

The latest LEP results have moved the mass of the SM Higgs boson well into the LHC domain. Various convincing simulation studies show that such a Higgs boson should be discovered at latest during the year 2010. Furthermore, the observation of the Higgs should directly provide a sufficient mass accuracy of ≈1–3% or better. Once the mass is known, different production and decay modes can be measured. Within the SM, especially valuable information, with accuracies of 5–10%, about the Higgs couplings to the $t\bar{t}$ quarks and to the $WW$ and $ZZ$ vector bosons can be obtained from the comparison of signals seen with the gluon–gluon fusion process and the vector boson fusion process.

One might thus conclude that, while most probably the SM Higgs discovery signatures are known, the perspectives of precision SM Higgs studies are just beginning to be exploited. This is especially true after the Higgs is discovered and its mass is known. The knowledge of the Higgs mass combined with more realistic understanding of the experimental LHC conditions should allow the detection of many additional Higgs signatures. Consequently, todays optimistic prospects of Higgs physics at the LHC might look even pessimistic, once the Higgs has been discovered at the LHC.

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